EXHIBIT NO 3

To examine the effect of grades and corrections for them to reduce the measurements to comparative power on different road surfaces when the truck is operated on other than level roads a number of calculations such as the following were made

On the assumption that the tractive resistance on a level road is 30 pounds per ton at 20 miles per hour, the average horsepower at the tire treads was calculated for runs up and down different grades from 0 to 5 per cent The corresponding average electric currents were calculated and plotted against the per cent grade as shown in Figure 11 From such calculations the conclusion is drawn that the correction on grades of 1 per cent or less is quite small and becomes large over grades of over 3 per cent

# INVESTIGATIONS OF AIR RESISTANCE ON AUTOMOBILES

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This report summarizes the results of investigations conducted during the summer of 1926 to ascertain whether the results of measurements of the air resistance that were determined by causing air to pass a stationary motor vehicle are applicable without changing the assumptions with reference to the impingement area, when the vehicle is moving through still or moving air A considerable amount of research has been conducted in this field through the utilization of research has been conducted in this field through the utilization of wind tunnels and either full sized cars or models thereof It was desired to apply the formulas developed in these researches to various problems of highway economics, thereby avoiding the necessity of measuring the air resistance of each individual vehicle employed on tractive resistance or fuel consumption studies

This investigation was conducted as a part of the program of highway research which is being conducted through cooperation between the U S Bureau of Public Roads and the Iowa Engineering Experiment Station at Ames, Iowa The research covered by this report was carried out by Prof Noah Wolfard of the Oklahoma College of Agriculture and the Mechanic Arts while he was a graduate student at Ames He was assisted by H H Hitchcock and H S Carter C H Crooks, Manager of the Fort Dodge, Des Moines and Southern Railway, made possible the particular method of investigation by furnishing a flat car for use in the set-up and providing a motor and crew to operate the field runs The very sympathetic and

efficient cooperation of the Fort Dodge Line is gratefully acknowledged.

The general scheme of the major investigation was conceived by Professor Wolfard. It was to place vehicles on a dynamometer mounting on an ordinary flat car and to measure the wind force against the mounted vehicle as the flat car and its load were pushed along a stretch of level track at various speeds. The several factors to be measured were: the component in the direction of travel of the force of air impinging against the mounted vehicles, the velocity with which the air passed the mounted vehicle and the direction of the air stream relative to the line of travel.

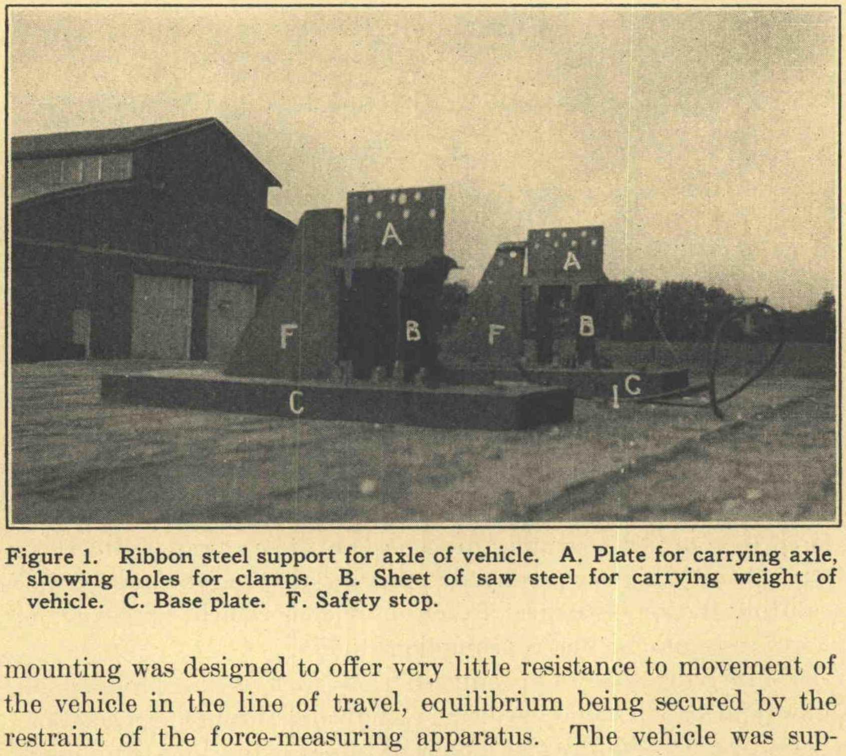


Figure 1. Ribbon steel support for axle of vehicle. A. Plate for carrying axle, showing holes for clamps. B. Sheet of saw steel for carrying weight of vehicle. C. Base plate. F. Safety stop.

mounting was designed to offer very little resistance to movement of the vehicle in the line of travel, equilibrium being secured by the restraint of the force-measuring apparatus. The vehicle was supported on four bearing blocks each of which was like that shown in Figure 1, except for the shape of the clamps for the axle of the

The force exerted on the vehicle by the air was obtained by mounting the vehicles on steel ribbon supports with an hydraulic dynamometer to take the thrust resulting from the air pressure. The vehicle. The flexural resistance of the strips of steel is very small for the amplitudes contemplated by the set-up. Calibration of the apparatus was expected to care for any small resistances in the blades and that such resistances did develop is clearly shown in the calibration curves, Figure 2

The force required to hold the vehicle in equilibrium against the air force was measured by the hydraulic method The backward thrust of the vehicle was received by a sylphon 4½ inches in

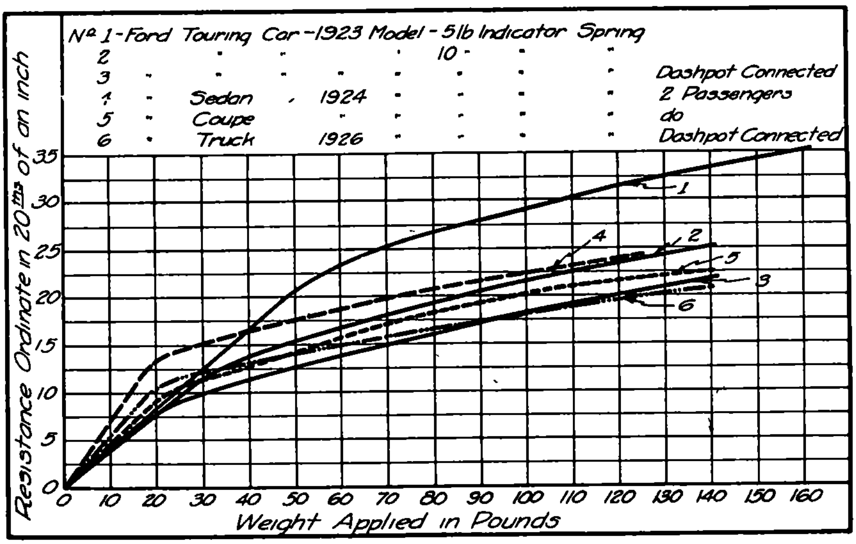


**Figure 2 Calibration curves for air resistance apparatus**

diameter This was connected by a one-half-inch pipe to a 2-inch sylphon which in turn actuated the spring and pencil movement of the pressure recording device A light lubricating oil was used to transmit the pressure, and since the two sylphons and connections comprised a closed system, the movement of the vehicle throughout the entire range of the measurements was small, generally about one-fourth inch as a maximum

An oil dash pot to minimize impact effects and safety lugs to prevent accidental displacement of the vehicle completed the set-up

The pressure developed in the sylphon was recorded on a continuous roll recording device which was geared to the axle of the flat car so that paper travel was a function of the distance the flat car traveled Through a clock mechanism, time intervals were recorded on the paper so that acceleration effects could be determined

The velocity of the wind was measured by means of a Robinson three-cup anemometr which was mounted on the forward part of the flat car and connected up to register electrically on the record sheet

The direction of the resultant air stream as the car moved over the course was determined by a streamer attached to the anemometer mounting and a scale on the floor of the car directly beneath the streamer. This was the most variable factor in the investigation and the one most difficult to determine with accuracy, facts that were anticipated before the investigation was undertaken. But it is felt

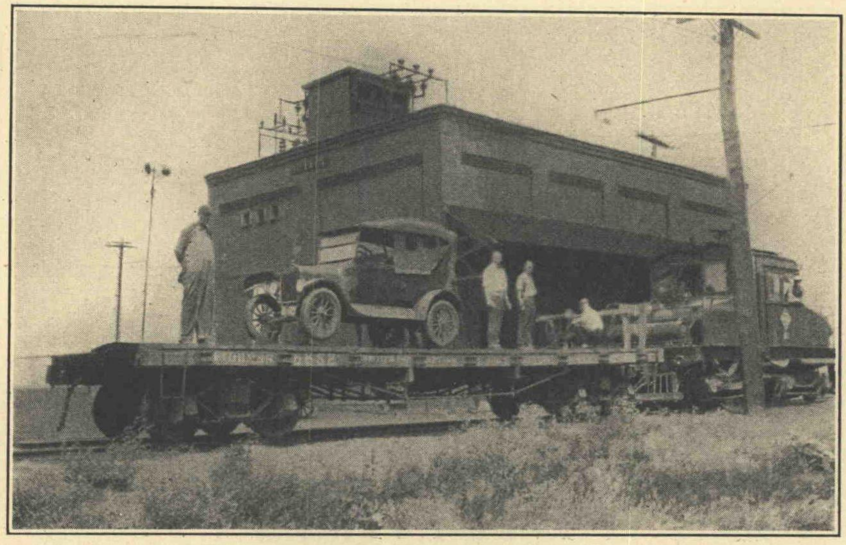

**Figure 3. Complete set-up ready for a test run**

that the direction of the air stream was determined with a degree of accuracy that renders the results of the investigation of great value for the purpose intended. Undoubtedly the wind direction varied along the course because of natural features of the land and yet this situation exists along most of the roads that are used by motor vehicles.

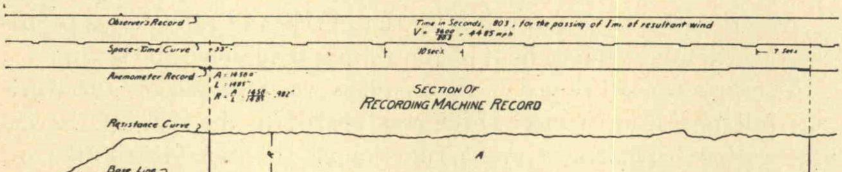


**Figure 4. Section of record of one of test runs**

The complete set-up is shown in Figure 3 and a section of the record from one of the runs is shown in Figure 4.

For each set of observations, the vehicle to be used was mounted on the apparatus on the flat car and then a calibration curve of the recording apparatus obtained. The flat car was then operated over the selected course as many times as was deemed necessary in order to secure the desired range of relative air velocities, which depended somewhat upon the intensity of the wind at the particular time

The record of the run was reduced as follows A tally mark appeared on the record for each mile of air that passed the anemometer The velocity of the air was calculated from the time record The average ordinate of the wind force diagram was determined by measuring the area of diagram corresponding to the passage of one mile of wind and dividing by the length The calculations are indicated by Figure 4 The resistance curves for a number of runs are shown in Figure 5

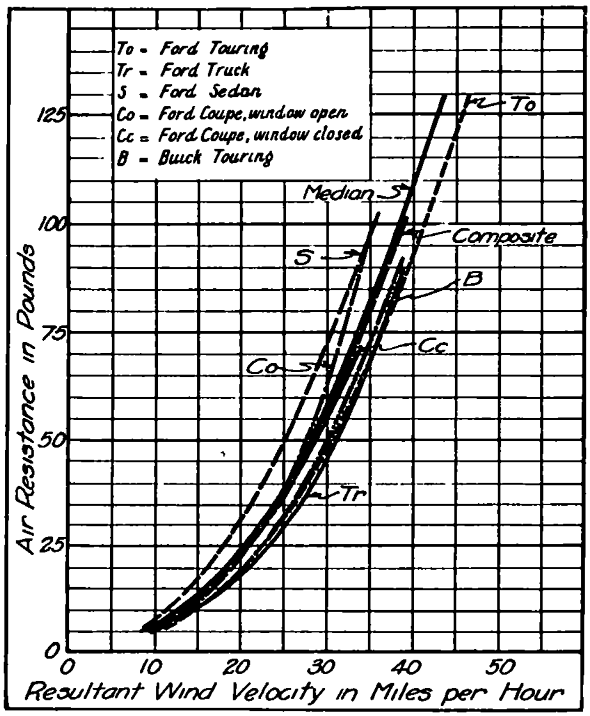


**Figure 5. Typical air resistance curves obtained during the investigation**

A number of investigations of the intensity of the air resistance on motor vehicles were reviewed and the results obtained by the several methods of observation may be compared by calculating the formula for a speed of 35 m p h and transforming to English Units throughout Table I is then obtained

While the formulas obtained by the several investigators agree quite closely as regards the *unit pressure* of the air on the vehicle, the calculation of *total* pressure on a moving automobile involves

TABLE I

COMPARISION OF FORMULAS FOR CALCULATING AIR RESISTANCE

$R_t$ = Total resistance on vehicle in pounds
A = Impingement area of vehicle in square feet
V = Air speed in miles per hour

| Investigator | Formula | $R_t$ at 35 m p h | Method of investigation |
|---|---|---|---|
| Rumpler [1] | $R_t = 00258AV^2$ | 60 55 | Wind tunnel experiments with models |
| Jaray [2] | $R_t = 00265AV^2$ | 91 62 | Wind tunnel experiments with models |
| Conrad [3] | $R_t = 0025AV^2$ | 79 62 | Wind tunnel experiments with full sized vehicles |
| Wolfard | $R_t = 00241AV^2$ | 76 75 | As outlined in this report |

[1] Rumpler, E "Das Auto in Luftstrom" Zeit f Flught U Motorl Schif Vol 15, No 3, pp 22-25, 1924

[2] Jaray, P "Die Leistungs Berechnung des Motorwagens unter besonderer Berucksightigong des Luftwiderstands" Motorwagen, Vol 25, No 29, pp 551-559, 1922

[3] Conrad, L E "Wind Resistance of Motor Vehicles" Public Roads, Vol 6, No 9, pp 203-206, 1925

some assumption with reference to the total area of vehicle subjected to the unit pressure This is arrived at in various ways by the several investigators and it is clearly apparent that no simple method can be employed if highly accurate results are to be secured Manifestly the shape of the vehicle will have considerable influence upon the area that will be subjected to air pressure and the shape of the area is also an important factor For exact results, the effective pressure area would be determined by wind tunnel methods for each design and expressed in terms of a percentage of the area of a rectangular or circular plate having an area equal to the projected cross-sectional area of the vehicle

For the purposes of this investigation it seems best to employ the form adopted by Conrad, since the various types of vehicles in use in the United States follow a fairly standard form Conrad determined the impingement area by photographing the front elevation of the vehicle and measuring the area with a planimeter and the area so determined is the "A" of his formula for air resistance Results so obtained are sufficiently exact for the calculations involved in most of the problems of tractive resistance of self-propelled vehicles In this form Conrad's formula would become $R_t = 00149\ AV^{2\ 14}$ and Wolfard's formula on the same basis is $R_t = 00167\ AV^{2\ 10}$

In each case $R_t$ is total air resistance in pounds, V the relative air velocity in miles per hour and A, the projected cross-sectional area of the vehicle

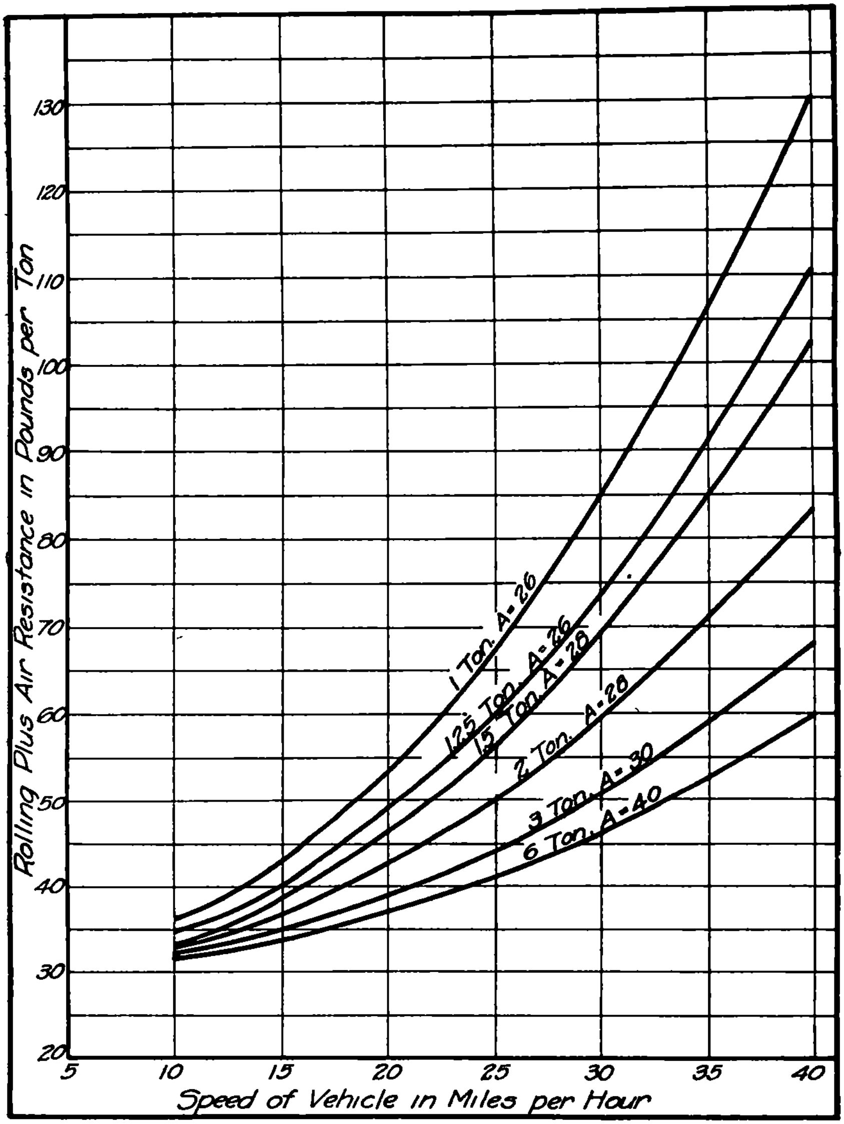


**Figure 6 Typical tractive resistance curves based on results of the investigation**

It must be remembered that the air resistance thus computed is in pounds per vehicle Rolling resistance is usually expressed in pounds per ton of weight and the air resistance as computed above must be reduced to pounds per ton by dividing by the weight of vehicle in tons For ordinary problems involving rolling resistance the factor A may be taken at 26 square feet for cars of standard design of United States manufacturers but for trucks and busses the actual area should be determined By way of illustrating the application of these factors to problems of tractive resistance, the diagram in Figure 6 has been prepared The rolling resistance is 30 pounds per ton and the diagram shows the magnitude of rolling plus air resistance in pounds per ton for vehicles of various weights and sizes.

## CONCLUSIONS

It has been demonstrated experimentally and theoretically that the exponent of V in the air-resistance formula should be 2 That Conrad obtained 2 14 for this exponent and Wolfard 2 10 may be attributed to small experimental errors For estimating the total air resistance on a motor vehicle, the formula can be used in the form

$$R_t = 0025\ AV^2$$

in which

$R_t$ = the total air resistance in pounds
A = the projected cross-sectional area of the vehicle in square feet.
V = the speed of the vehicle in miles per hour